AD-A146 517 THE HEMP (HIGH-ALTITUDE ELECTROMAGNETIC PULSE) RESPONSE 1/1
OF A LONG TRANSMI..(U) HARRY DIAMOND LABS ADELPHI MD
R P MANRIQUEZ ET AL. SEP 84 HDL-TR-2051

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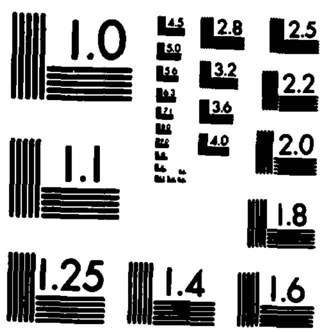

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September

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The HEMP Res... on ... in the Earth

by Rolando P. M...
Ronald J. Reyze...
John F. Sweton...

...Command

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER HDL-TR-2051	2. GOVT ACCESSION NO. AD-A146 517	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) The HEMP Response of a Long Transmission Line Buried in the Earth		5. TYPE OF REPORT & PERIOD COVERED Technical Report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Rolando P. Manriquez Ronald J. Reyzer John F. Sweton		8. CONTRACT OR GRANT NUMBER(s) PRON: WS3—8301WSA9 MIPR: HC1001-3-401
9. PERFORMING ORGANIZATION NAME AND ADDRESS Harry Diamond Laboratories 2800 Powder Mill Road Adelphi, MD 20783-1197		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Ele: 33126K
11. CONTROLLING OFFICE NAME AND ADDRESS National Communications System (DCA) Office of the Manager Washington, DC 20305		12. REPORT DATE September 1984 13. NUMBER OF PAGES 24
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES HDL Project No. E313E3 DRCMS Code: 33126K		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) HEMP Transmitted E field below ground, Conductivity, Dielectric constant, Distributed source, and LPN model REPS Matrix tridiagonalization.		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This paper documents the calculation of the current coupled to a long, buried, insulated cable excited by a horizontally polarized plane-wave electromagnetic pulse (EMP) field. This result is compared to the current measured on a similar long, buried cable located approximately 800 ft from a radiating, horizontally polarized EMP simulator having the same driving horizontal field. (Original... signed ... included)		

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FOREWORD

The National Communications System (NCS) in response to Presidential Directive/NSC-53, "National Security Telecommunications Policy," is funding a comprehensive program on the effects of nuclear weapons on selected telecommunications systems. A portion of this effort is directed at determining the high-altitude electromagnetic pulse (EMP) vulnerability of the commercial Bell Telephone T1 Carrier system, and at developing a T1 Carrier system specifically engineered to be EMP hard. The work described in this report was performed in support of these efforts.

CONTENTS

FIGURES

1. INTRODUCTION

Investigators have measured the current induced by an electromagnetic pulse (EMP), as produced by the repetitive EMP simulator (REPS), on a long, terminated, insulated cable buried at a shallow depth near the air-earth interface. The measured current is compared with analytical predictions of the current induced on the same cable excited by an exoatmospheric EMP. The main objectives of this paper are to evaluate the plane-wave electromagnetic field propagation through a linear, isotropic, and homogeneous conducting medium; to represent the EMP coupling to the buried cable by the equivalent distributed-source, lumped-parameter network (LPN) model; and to compare the results to experimental measurements using an EMP simulator.

The reflection and transmission of electromagnetic waves at a plane surface between the air and earth media are familiar phenomena. It is assumed in this study that the incident wave, generated in free space, is a linearly polarized plane wave (constant amplitude and phase), and the earth boundary is treated as a semi-infinite, linear, homogeneous, isotropic, and conducting medium.

The incident electric field above the earth is computed based on the measured magnetic field above ground. Subsequently, the transmitted electric field below ground is computed through the use of Maxwell equations and Fresnel coefficients. The procedure used to calculate the transmitted fields from measured magnetic field data is reported in a companion paper.[1] The cable under study is a 1200-ft section of shielded cable that is terminated in a "short circuit" to ground at both ends of the cable. The cable is buried 18 in. below the surface of the earth. A cross section of the shielded cable is shown in figure 1. The incident field is horizontally polarized and arrives at the earth boundary at an elevation angle of 3 degrees. The earth's parameters of conductivity, σ, and dielectric permittivity, ϵ, are derived as a function of frequency based upon the universal impedance for soils, generated by Longmire and Smith,[2] and an assumed moisture content of 10 percent by volume.

The cable has been arranged in an arc from the center of a point-source EMP simulator, as shown in figure 2. Thus, the peak EMP signal arrives at all points along the cable at the same time. The particular simulator being used in the experiment is the Army's REPS, a horizontally polarized dipole radiator driven by a 1-MV repetitive pulse generator. The current is sensed with a Stoddard clip-on current probe (model 91550-3), and the data are recorded on a fiber-optic system and transmitted to an instrument van, where they are converted back to an electrical signal and monitored with a Tektronix 7912 oscilloscope. The data are also digitized, processed, and stored on disk for future use.

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[1] *Rolando P. Manriquez and John F. Sweton, An Indirect Measure of Below-Ground Electric Field, Conductivity, and Dielectric Constant, Harry Diamond Laboratories, HDL-TR-2052 (September 1984).*

[2] *C. L. Longmire and K. S. Smith, A Universal Impedance for Soils, Mission Research Corp., Santa Barbara, CA, Contract No. DNA5001-75-C0094 (October 1975).*

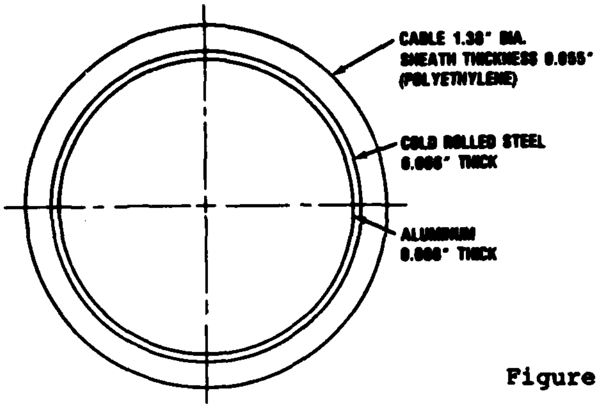

Figure 1. Cross section of shielded cable.

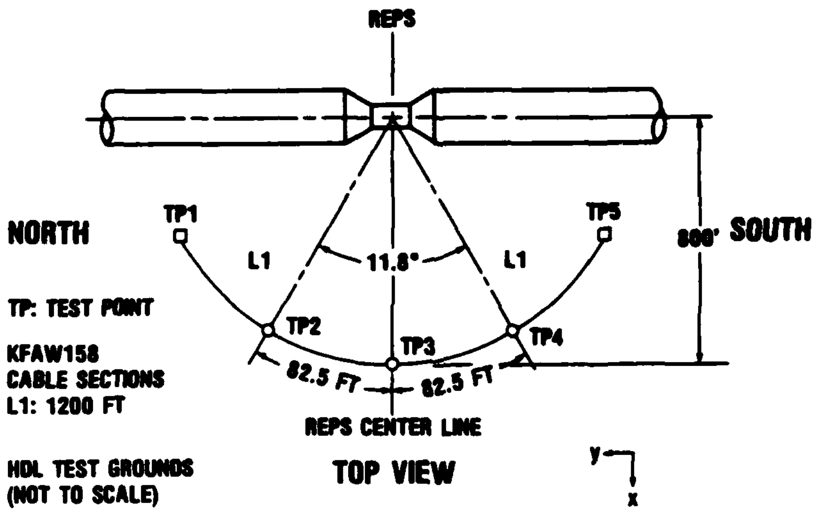

Figure 2. Test configuration for HDL cable coupling studies.

The electrical short circuit at the ends of the cable is achieved by the use of a calcium chloride salt solution poured into a 3 × 3 × 3 ft pit containing a 6-ft grounding rod that is attached to the cable sheath by a standard telephone press-fit connector. The electric field incident on the cable is obtained by the use of the total magnetic field measured at five points along the length of the cable. An attempt to monitor the electric field at 18 in. below the surface of the earth is documented elsewhere.[1]

[1] *Rolando P. Manriquez and John F. Sweton, An Indirect Measure of Below-Ground Electric Field, Conductivity, and Dielectric Constant, Harry Diamond Laboratories, HDL-TR-2052 (September 1984).*

2. BURIED-CABLE RESPONSE ANALYSIS

The analytical method used to predict the response of the buried cable is similar to the methods used in earlier work.[3,4] The incremental section of the equivalent distributed-source LPN model is shown in figure 3. This model incorporates frequency-dependent passive elements. The voltage, V_i, is the transmitted E-field for each incremental section. The impedance for each incremental section consists of the ground impedance (Z_g), cable impedance (Z_i), and the inductive reactance (Z_L) of the insulation gap. The admittance for each incremental section consists of the capacitive susceptance (Y_d) of the insulation in series with the admittance (Y_g) of the ground. Thus, the transmission-line parameters are[3]

$$Z_g(\omega) = \frac{\omega\mu_o}{8} + \frac{j\omega\mu_o}{2\pi} \log\left(\frac{\sqrt{2}\delta_g}{\gamma_o b}\right) \quad , \tag{1}$$

$$Z_i(\omega) = \frac{(1 + j)T/\delta_c}{2\pi a\sigma_c T} \coth\left[(1 + j)T/\delta_c\right] \quad , \tag{2}$$

$$Z_L(\omega) = \frac{j\omega\mu_o}{2\pi} \log\left(\frac{b}{a}\right) \quad , \tag{3}$$

$$Y_g(\omega) = \frac{2\pi\sigma_g}{\log\left(\frac{\sqrt{2}\sigma_g}{\gamma_o b}\right)} + j\,\frac{2\pi\varepsilon_g}{\log\left(\frac{\sqrt{2}\delta_g}{\gamma_o b}\right)} \quad , \tag{4}$$

$$Y_d(\omega) = \frac{2\pi\sigma_d}{\log\left(\frac{b}{a}\right)} + j\,\frac{\omega 2\pi\varepsilon_d}{\log\left(\frac{b}{a}\right)} \quad , \tag{5}$$

where

$\delta_g = 1/\sqrt{\pi f \mu_o \sigma_g}$ = skin depth in the ground,

$\delta_c = 1/\sqrt{\pi f \mu_o \sigma_c}$ = skin depth in the shield,

σ_g = conductivity of the ground,

σ_c = conductivity of the shield,

σ_d = conductivity of the dielectric,

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[3] *E. F. Vance, Coupling to Shielded Cables, John Wiley and Sons, Inc. (1978).*

[4] *Michael S. Bushell, Rolando P. Manriquez, George Merkel, and William D. Scharf, Aurora Test Cell Electron Beam Environment--Response of Large Loop, IEEE Trans. Nucl. Sci. NS-30, No. 6 (December 1983), 4558-4563.*

ε_g = dielectric constant of the ground,

ε_d = dielectric constant of the protective jacket of the cable,

$\mu_o = 4\pi \times 10^{-7}$ H/m,

γ_o = 1.781 = Euler's constant,

b = outer radius of the insulation,

a = outer radius of the cable shield, and

T = thickness of the shield.

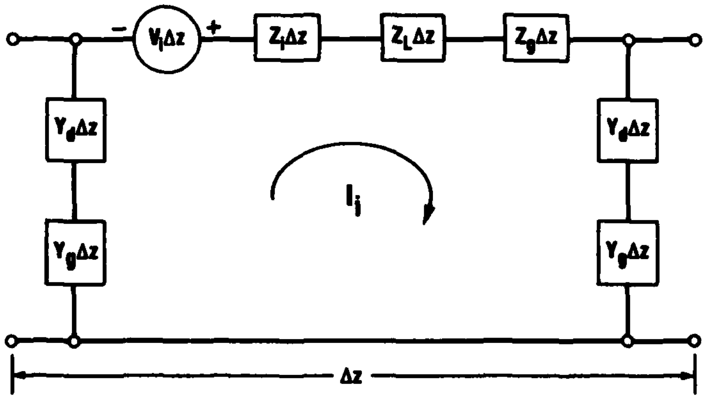

Figure 3. Incremental π section of equivalent distributed-source lumped-parameter network model of buried cable.

The transmission-line response is obtained by the implicit method.[5] At each increment along the line, the current is determined by solving the matrix equation

$$[Z][I] = [V] \;, \tag{6}$$

where [Z] is the impedance matrix, and [I] and [V] are the vector forms of the currents and voltages, respectively. The impedance matrix is expressed as a set of [Z] coefficients and can be found by the application of Kirchoff's current and voltage law to the equivalent transmission line. The elements of the voltage matrix [V] are the source terms for the transmission line, as shown in figure 3. Hence, equation (6) is expanded in the form[5]

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[5] *B. Carnahan, H. A. Luther, and J. O. Wilkes, Applied Numerical Methods, John Wiley and Sons (1969), 440-442.*

$$
\begin{aligned}
b_1 I_1 + c_1 I_2 \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad &= V_1 \\
a_2 I_1 + b_2 I_2 + c_2 I_3 \qquad\qquad\qquad\qquad\qquad\qquad &= V_2 \\
a_3 I_2 + b_3 I_3 + c_3 I_4 \qquad\qquad\qquad\qquad &= V_3 \\
\cdots \qquad\qquad\qquad\qquad\qquad & \\
a_i I_{i-1} + b_i I_i + c_i I_{i+1} \qquad\qquad &= V_i \\
\cdots \qquad\qquad\qquad & \\
a_{n-1} I_{n-2} + b_{n-1} I_{n-1} + c_{n-1} I_n &= V_{n-1} \\
a_n I_{n-1} + b_n I_n &= V_n \quad ,
\end{aligned}
\tag{7}
$$

where the [Z] coefficients are

$$
\begin{aligned}
b_1 &= Z_1 + Z_2 \quad , \\
c_1 &= -Z_2 \quad , \\
a_{n-1} &= -Z_{2n-2} \quad , \\
b_{n-1} &= Z_{2n-1} + Z_{2n-2} + Z_{2n} \quad , \\
c_{n-1} &= -Z_{2n} \quad , \\
a_n &= -Z_{2n-2} \quad , \\
b_n &= Z_{2n-1} + Z_{2n-2} + Z_{2n} \quad .
\end{aligned}
$$

Note that $Z_{odd} = Z(\omega)$, $Z_{even} = 1/Y(\omega)$, $V_i = E_i(\omega)\Delta z$, and n = total number of sections.

The set of the [Z] coefficients a, b, and c alone is called the tridiagonal matrix. The system matrix (eq (7)) is readily solved by a Gaussian elimination method with a maximum of three variables per equation, and the solutions can be expressed very concisely. The recursion solutions of equation (7) for each frequency yield the currents through each branch.

The cable response obtained with the frequency-domain LPN model used in this study was then compared to two solutions based on (1) Vance's approach[3] using constant or frequency-dependent σ and ε and (2) the time-domain LPN

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[3]*E. F. Vance, Coupling to Shielded Cables, John Wiley and Sons, Inc. (1978).*

approach[4] using constant σ and ε. The number of incremental sections was increased until good agreement between the results of the LPN models and the results of Vance's approach was achieved for constant σ and ε. The advantages of the frequency-domain LPN technique are that (1) σ and ε can be functions of frequency and moisture content and (2) different E-field values can be used for each incremental section. Finally, the solution of the short-circuit current, $I_{sc}(w)$, at the last branch is inverse Fourier transformed[6] to yield the desired time response, $I_{sc}(t)$, at the end of the buried cable.

3. DISCUSSION OF RESULTS

The magnetic field, $H_x(t)$, was measured using an H-field sensor at a height of 1 m above ground and located on one of the faces of the Stanford Research Institute cubical sensor box.[7] The digitized waveforms of measured $H_x(t)$ at test points TP1 to TP5 (see fig. 2) are shown in figure 4. The transmitted electric fields, E(t), below ground at TP1 to TP5 are shown in figures 5 to 7 for constant values of conductivity σ = 0.001, 0.007, and 0.02 mho/m with dielectric constant ε_r = 15. These figures show the early-time variations of E(t) up to 1 µs. Although the calculations were carried to 5 µs, all the E(t) beyond 1 µs are small. As shown in figures 5 to 7, both amplitude and waveform are significantly affected by changes in conductivity but are relatively insensitive to changes in dielectric permittivity.

In reality, the conductivity and dielectric permittivity are functions of frequency and depend upon the moisture content of the soil. Longmire and Smith's universal formula[2] is used to determine σ and ε_r for variation of moisture content. These are shown in figures 8 and 9. Figures 10 and 11 show the effects of these frequency functions for 10- and 25-percent moisture content, respectively, on E(t) at TP1 and TP5.

The transmitted fields, conductivity, and dielectric permittivity are input to the frequency-domain LPN computer program used to calculate the short-circuit current response of the buried cable. The impedance and admittance parameters were increased by a factor of 2 to obtain a better correlation between the measured and calculated short-circuit current at early times.

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[2]*C. L. Longmire and K. S. Smith, A Universal Impedance for Soils, Mission Research Corp., Santa Barbara, CA, Contract No. DNAS001-75-C0094 (October 1975).*

[4]*Michael S. Bushell, Rolando P. Manriquez, George Merkel, and William D. Scharf, Aurora Test Cell Electron Beam Environment--Response of Large Loop, IEEE Trans. Nucl. Sci. NS-30, No. 6 (December 1983), 4558-4563.*

[6]*Alfred G. Brandstein and Egon Marx, Numerical Fourier Transform, Harry Diamond Laboratories, HDL-TR-1748 (September 1976).*

[7]*B. C. Tupper, R. H. Stehle, and R. T. Wolfram, EMP Instrumentation Development, Stanford Research Institute, report 7990, under contract to HDL, Contract DAAK02-69-C-0674 (June 1972).*

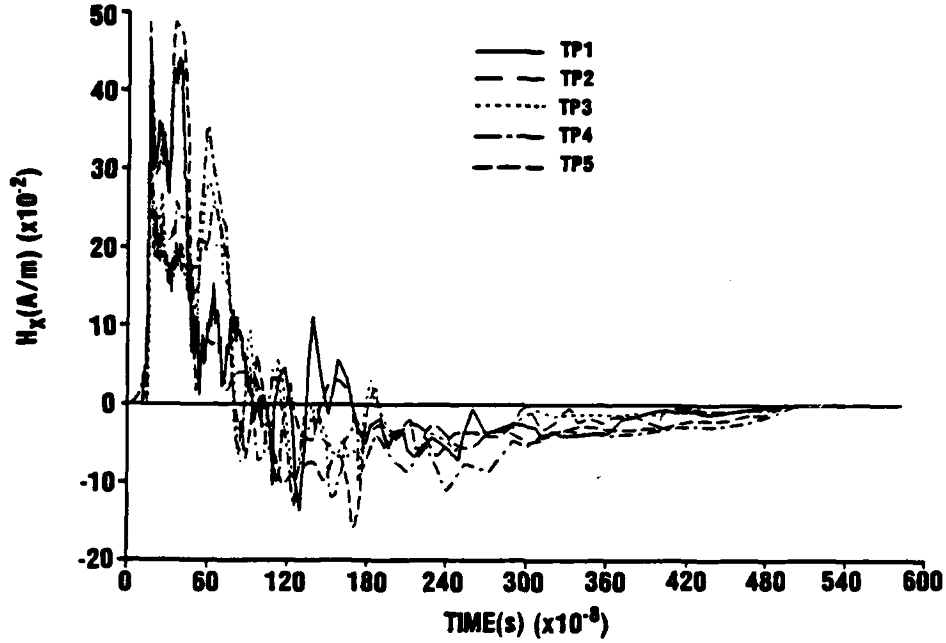

Figure 4. Digitized waveforms of measured $H_x(t)$ at TP1 to TP5.

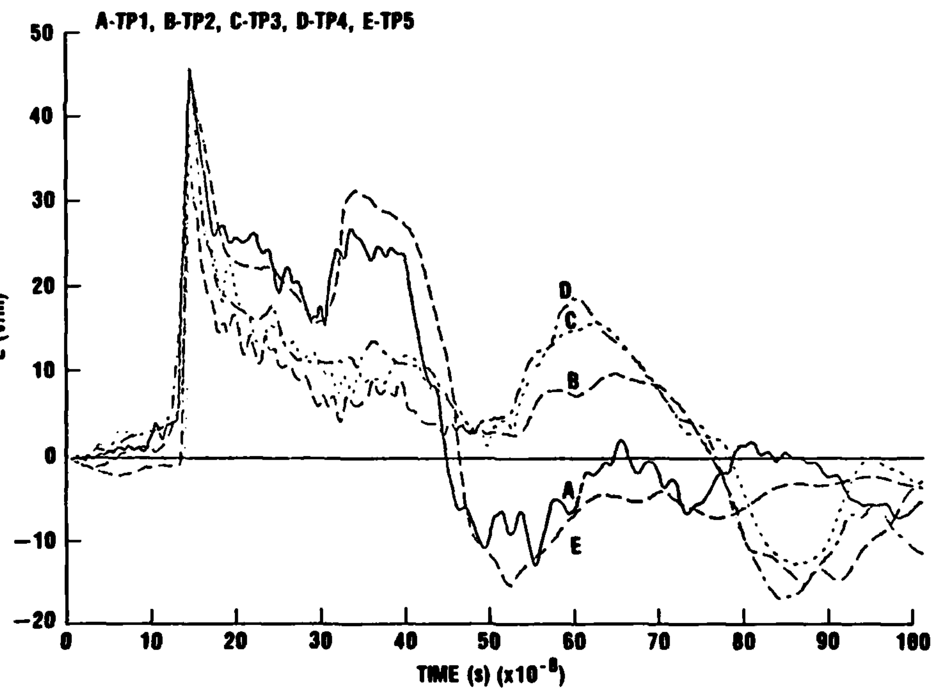

Figure 5. Transmitted electric field at TP1 to TP5 with σ = 0.001 mho/m and ϵ_r = 15.

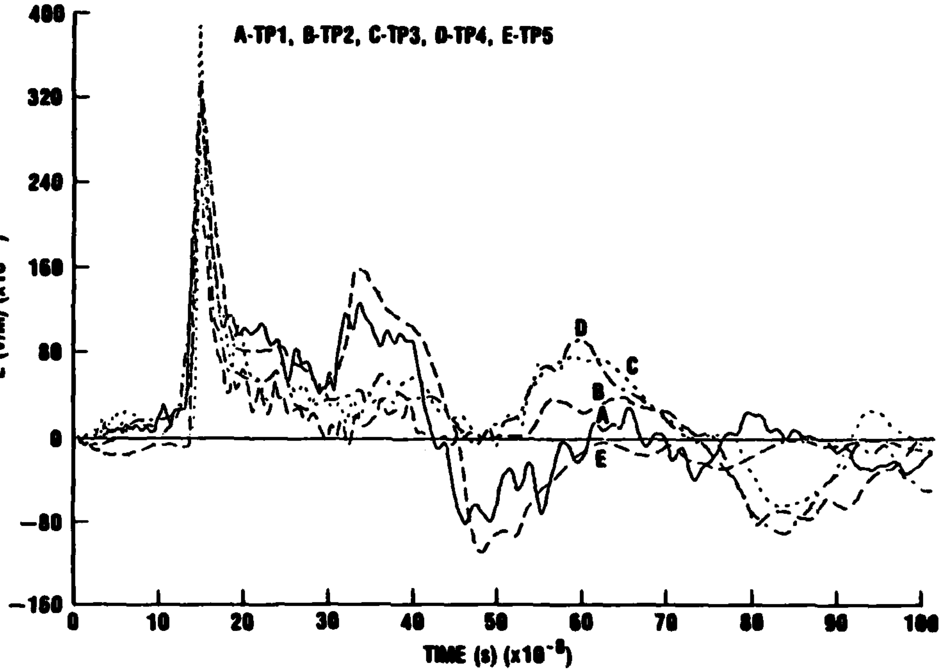

Figure 6. Transmitted electric field at TP1 to TP5 with σ = 0.007 mho/m and ε_r = 15.

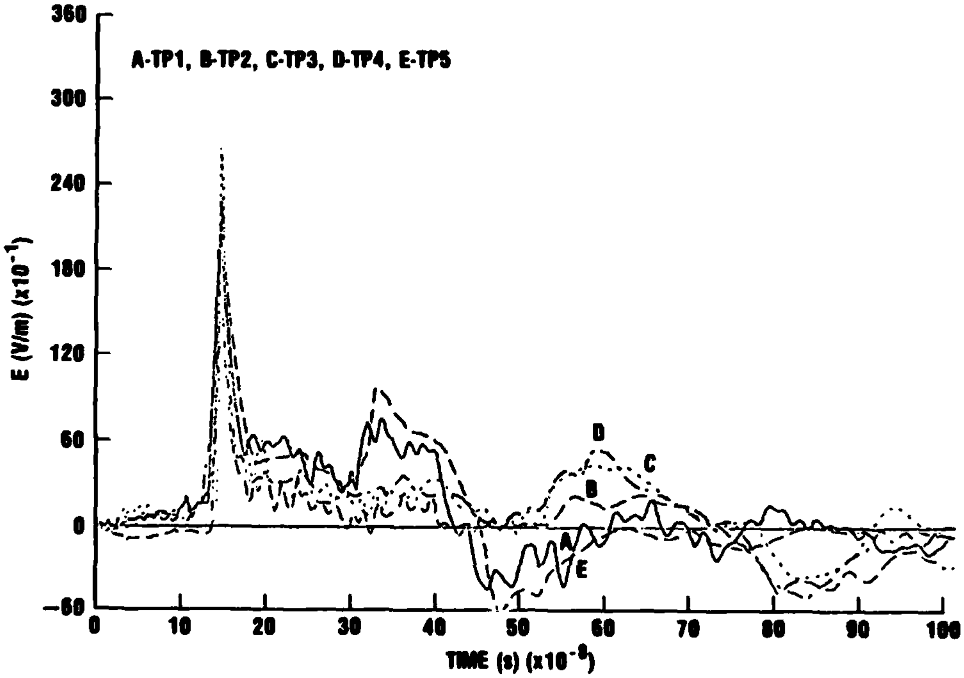

Figure 7. Transmitted electric field at TP1 to TP5 with σ = 0.02 mho/m and ε_r = 15.

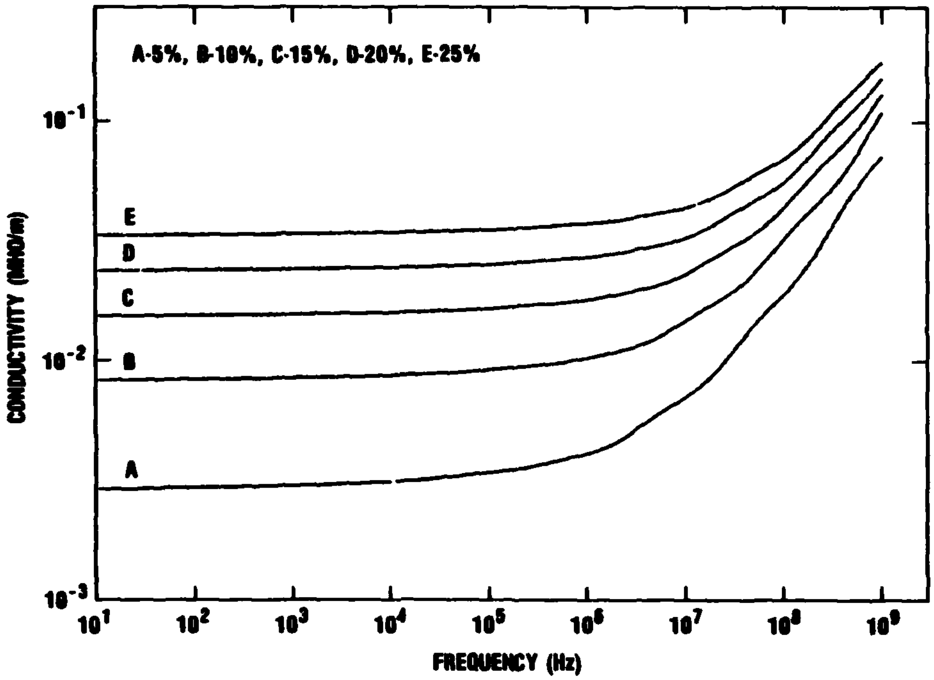

Figure 8. Soil conductivity with varying moisture content (5 to 25 percent).

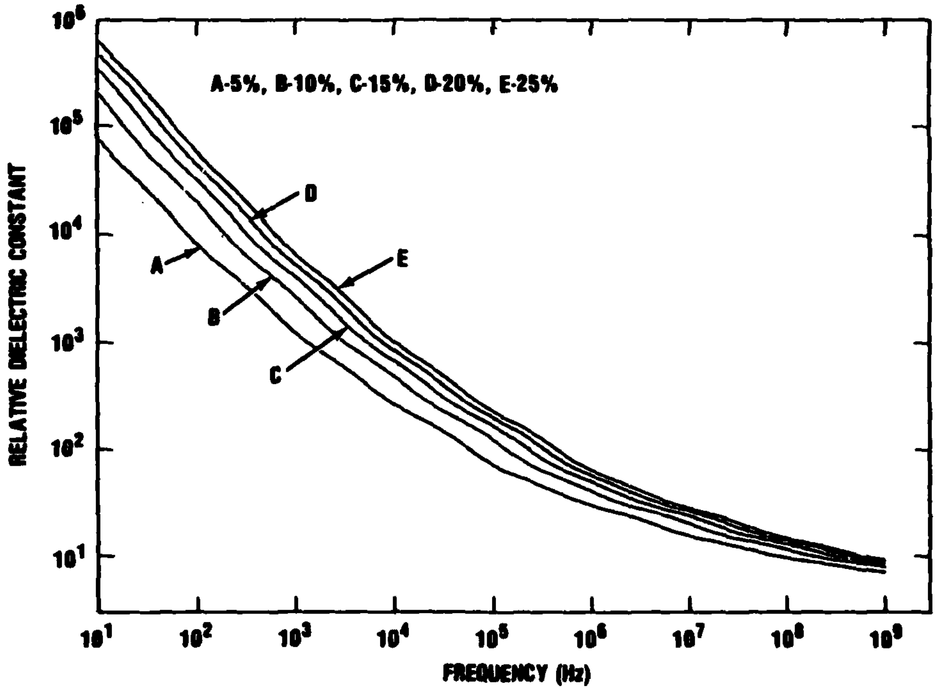

Figure 9. Soil dielectric constant with varying moisture content (5 to 25 percent).

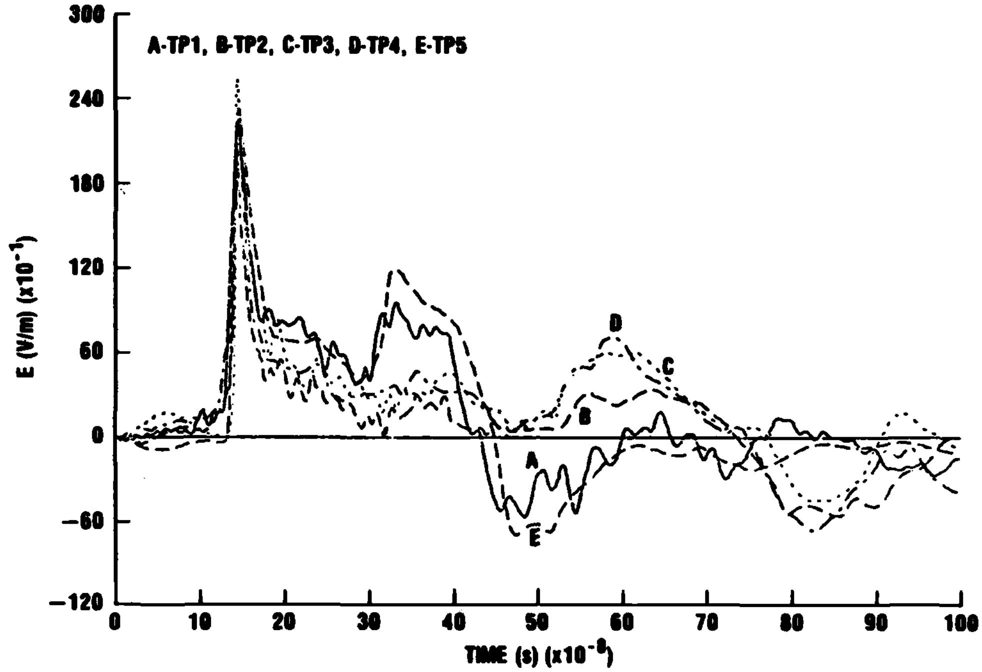

Figure 10. Transmitted electric field at TP1 to TP5 with 10-percent moisture content.

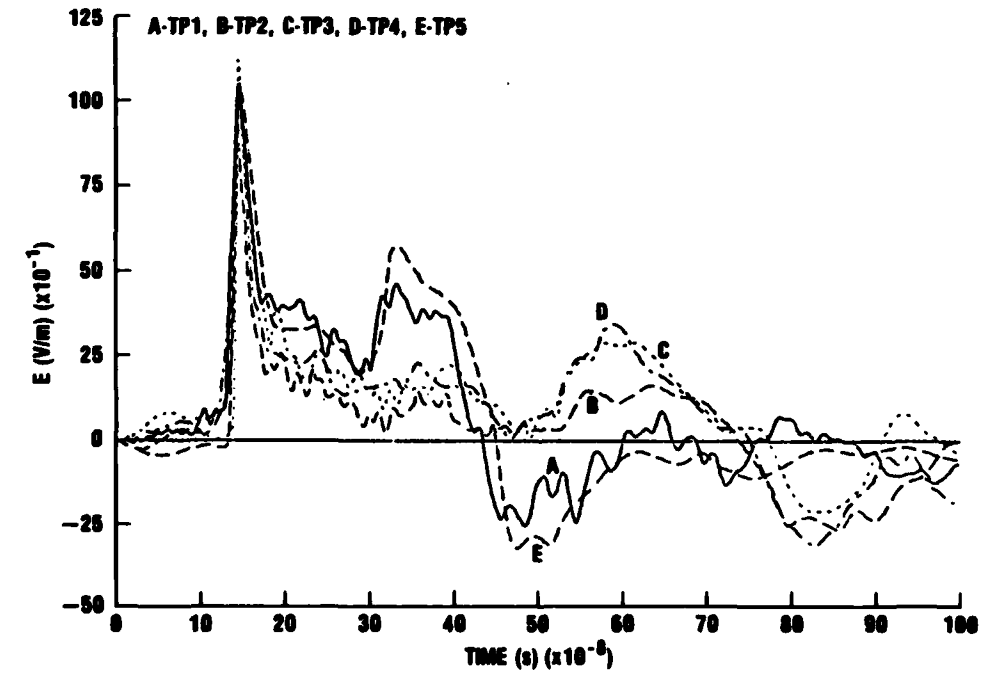

Figure 11. Transmitted electric field at TP1 to TP5 with 25-percent moisture content.

Figure 12 compares the measured and calculated E(t) with σ and ε_r varying with frequency at 5-, 10-, and 25-percent moisture content. Values of σ = 0.007 mho/m, ε_r = 15, and 10-percent moisture content yield close agreement between the measured and LPN data at early times. These values were also determined empirically from correlation between the measured and calculated transmitted electric fields below ground, as cited elsewhere.[1] The comparison between the measured and calculated $I_{sc}(t)$ with σ = 0.001, 0.007, and 0.02 mho/m and ε_r = 15 are shown in figure 13. Figure 14 shows the late-time measured short-circuit current.

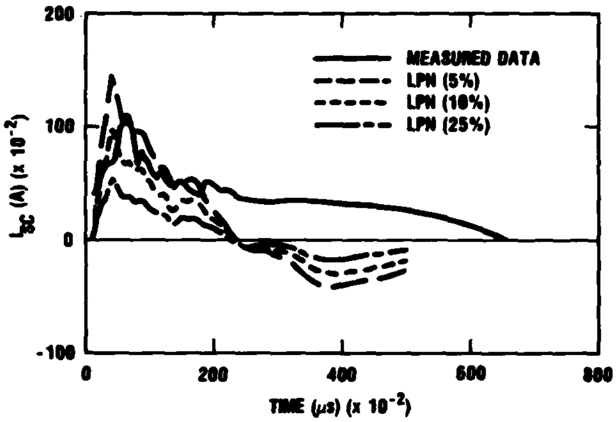

Figure 12. Comparison between measured and LPN data with varying moisture content (σ and ε_r both functions of frequency).

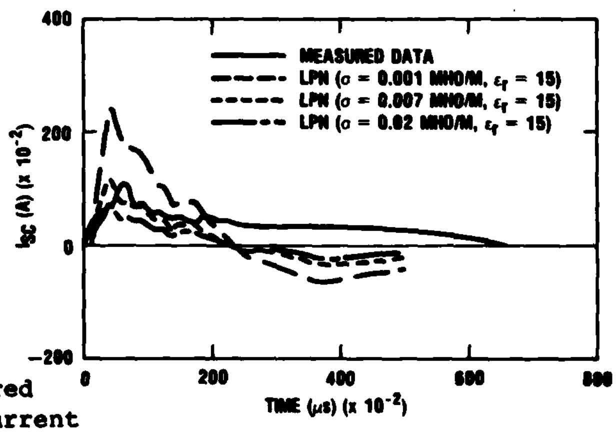

Figure 13. Comparison between measured and LPN short-circuit current with representative constant values of σ and ε_r.

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[1]*Rolando P. Manriquez and John F. Sweton, An Indirect Measure of Below-Ground Electric Field, Conductivity, and Dielectric Constant, Harry Diamond Laboratories, HDL-TR-2052 (September 1984).*

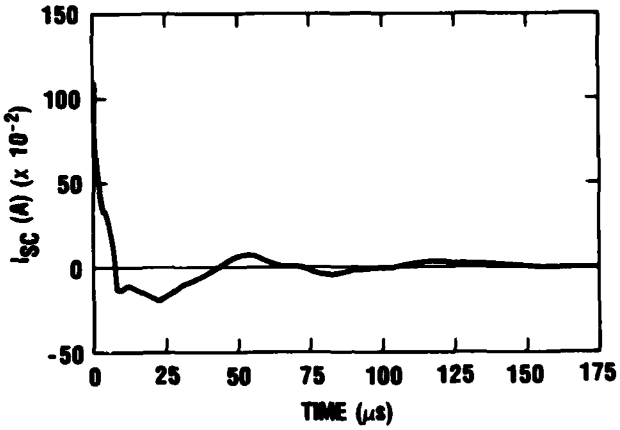

Figure 14. Late-time measured short-circuit current.

4. CONCLUSION

It can be seen from the data (fig. 12) that the risetime and amplitude of the calculated and measured currents are in good agreement. However, for the late-time waveshape (fig. 12 and 14), there is a significant divergence between the measured and calculated data. The reason or reasons for this disagreement are not known, but it is clear that if this discrepancy results from the (near-field) proximity of the cable to the simulator (a likely possibility), then the result to distributed system testing could be significant. On the other hand, if this discrepancy is the result of some factor not adequately accounted for in the analytic calculation, the result to distributed system analysis would be similarly significant.

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